Draft CEC PIER-EA Discussion Paper

Climate Observations, Models, and Diagnostics Needs for California

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Disclaimer

The purpose of this paper is to inform discussions among CEC staff, other state agency staff, non-governmental representatives, representatives of academia and other stakeholders regarding the state of the research on climate observations, models, and diagnostics needs in California. In particular, this discussion paper will identify gaps in our understanding and recommendations for future research initiatives with the end goal of supporting informed and systematic planning for climate change. Note that this discussion paper is not a research proposal and does not include recommendations regarding specific research projects.

1.0 Description of Research Topic

Building upon the IPCC Reports (e.g., 2008) and other global and regional evidence, an unfolding history of assessments have consistently indicated that global climate change will have multifold effects in California, including warming, changes in the hydrologic system, rises in sea level, and possibly changes in the frequency or intensity of extreme weather events (Field et al., 1999, Barnett et al., 2004, Hayhoe et al., 2004, Cayan et al., 2007, Franco et al., 2007). California's setting in a highly variable Mediterranean climate regime and its coast-interior gradients and complex topography combined with seasonal temperatures that hover near freezing, cause it to have great sensitivity to climate warming (e.g., Bales et al., 2005). Impacts are projected to spread across many of California's economic and social sectors, and will also present challenges to California's diverse ecosystems. To better prepare to adapt and possibly mitigate these changes, California can make use of its rich scientific and technical presence at government, private, non-profit and university centers. As described in this discussion paper, to provide high quality information to California's government and other decision makers will require an arsenal of observations, models and considerable work to diagnose and understand them. This document updates and expands the PIER White Paper by Lawrence Gates (2003) that discussed and laid out a course for a CEC regional climate modeling activity. To know and articulate all of these requirements is, of course, a great challenge, so this document only presents highlights and an approach to addressing them.

2.0 Climate observations

Careful, comprehensive monitoring of climate, taken broadly, and its impacts is necessary to provide California the information it will need to answer fundamental and applied questions relating to how we should mitigate and prepare for climate changes. Amongst these questions:

- How has climate changed in California's past?
- What is the current status of California's climate?
- How is California's climate changing?
- Why is it changing?
- What locations and systems are most vulnerable?
- What are the interconnections and impacts?
- Are models used to simulate climate changes and impacts working realistically?

To answer these questions requires a stream of continuing observations along with a well maintained archive that provides documentation and access to the data—in short, a California climate observation system. Such a system requires long-term commitments to maintaining specialized climate stations that provide climate quality data in key locations as well as long-term agreements for the accumulation and sharing of climate data from other agencies and sources. Such a system must aim to acquire climate quality observations from stations that record the ambient climate consistently and regularly through future decades, that minimize local and instrumental effects over a long term, and that are flexible enough to allow incorporation of new sensors and observations. The basic requirements have been laid out by Trenberth, Karl, and Spence (2002) in their *Ten Principles of Climate Observing* and in Redmond (2003, 2007).

Climate monitoring is too expensive for a single agency or even a single entity (State of California) to underwrite. Many important observations have been designed at least partly to satisfy needs that are not related to climate—e.g. snow measurements in California are made to gauge seasonal water supplies, and only recently have become a standard climate index. This means that, to acquire the information needed for climate purposes, the climate community in the State must collaborate with other agencies, often ones with operational missions. Also, California's climate and climate-relevant measures are affected or determined by conditions and phenomena that take place outside the State—this brings in the requirement of information streams from external sources.

Questions about climate often require not only current day or current month/year information, but also a historical record to put the present day (or projected future) climate into perspective. Notably, there are three major archives of State climate data:

- California State Climatologist and the CDEC system;
- Western Regional Climate Center;
- National Climatic Data Center.

2.1 Suggestions

- Develop climate observations in California's sensitive, vulnerable and sparsely observed areas. Examples include coast-inland sections and transition zones, valley-mountain gradients, and rain-snow transitions.
- Augment traditional measurements of air temperature, precipitation, and winds with new observations: e.g., soil moisture, aerosols, radiation, GPS water vapor,

water temperatures, etc., in order to track the multivariate climate changes that are expected.

- Place greater emphasis on remote sensing of surface, snow, vegetation, and atmosphere; develop operational monitoring products describing variations of snow cover, snow albedo, vegetation greenness and vigor, seasonal wetlands and inundation, etc., at State and watershed scales.
- Develop more pervasive real time observation capacity—communications are a key technology that enables more effective use, analyses, and maintenance of the observing system.
- Collaborate across agencies (federal, local, private, etc.) to collect observations.
- Periodically (every 5 years), evaluate and publish an Assessment of state of the State's climate observation system, perhaps in concert with an assessment of the State's recent climate.
- Build hierarchical observation networks, to include selected numbers of highest quality sensors and stations, and denser numbers of lesser quality stations.
- Install profilers and radars to monitor vertical structure of the atmosphere.
- Increase observations of urban climate (e.g., temperature, humidity, radiation, winds, precipitation).
- Integrate efforts with the coastal ocean monitoring community.
- Conduct a California climate-observation-system summit: work with the State Climatologist and others to communally assess and identify future monitoring needs and opportunities.
- Access and collect pertinent paleoclimate records, particularly high resolution records that provide proxy records of recent Holocene climate in California; support integration of paleoclimatic records across and between California's critical climate gradients, linking paleoclimates of the mountains with valleys, the coast with the inland areas, more fully than has been the case to date.
- Fund climate data managers to organize climate observing system, including climate archive.
- Work to develop "Citizen Science" observing programs. E.g., cooperative weather observers, phonological observers.
- Work with climate impact and other communities to develop non-traditional retrospective and ongoing datasets needed to evaluate climate impacts.

3.0 Modeling California's Climate

3.1 Description of Modeling Research Topic

Modeling research is needed to ensure the development and improvement of numerical models to simulate, predict, and diagnose the past and future climate (CCSP, 2008). Such modeling research is needed for California (Gates, 2003), similar to other regions, globally as well as nationally. Such research should determine the uncertainties of the simulations due to model differences, and compare dynamical model results with statistical methods. Dynamical models of climate changes—global and regional—are among the most powerful tools to predict and understand complex interactions between ocean, land, and atmosphere on climate time scales. Such models provide complete data coverage, based on first principles of climate dynamics, at various spatial and temporal scales not directly obtainable from observations, nor unduly biased by past conditions, so that the data are especially useful for both diagnosis of past climatic effects and prediction of future conditions.

In this discussion, our focus is on *regional* models. Global models, of course, are essential to providing the broader patterns and forcings for regional climate and climate models. But because global modeling is undertaken at a number of international and national centers, and because the work to develop and support them is very expensive, it has been decided that the best investment for California should be focused on regional modeling.

Several areas of research, related to regional modeling are required:

- "Downscaling," which is the use of methodologies to infer higher resolution information from global models results for applications on the regional and local scales. Several downscaling methods already have seen much use in applications focusing on water resources and surface climate change, but improvements are needed to determine how well models simulate the recent observational period;
- Systematic biases, both from the forcing GCMs and in regional model simulations, e.g., in precipitation. On smaller geographic scales, when compared against the current climate, the simulated climate varies substantially from model to model. The recent PIER-sponsored REBI study notes that "an average over the set of models clearly provides climate simulation superior to any individual model," and concludes that "no current model is superior to others in all respects, but rather different models have differing strengths and weaknesses;"
- What current models can simulate well, and where models need improvements.

This is crucial to assure that future climate projections are used appropriately.

3.2 Some Highlights of PIER Modeling Research

Under CEC PIER sponsorship, some important California regional model developments and experiments have been conducted. This program has achieved a greater degree of collaboration across several California institutions, and has also promoted a stronger degree of collaboration with other projects funded by NOAA, DOE, and NASA.

Two projects were undertaken involving a group of modelers from UCSB, UCSC, LBNL, and SIO. These projects accomplished their original objectives, and the results have been published in PIER reports and refereed journals. Some of the institutions performed additional research based on the intercomparison study, and those results were also published in refereed journals. Particularly, in the intercomparison of the downscaling of reanalysis, statistical method was also included for comparison. This is the first time the statistical method has been compared with the dynamical method in exactly the same conditions.

The impact of the change of vegetation and irrigation on near-surface temperature was studied by (Kueppers et al., 2006). This project was jointly undertaken by Scripps (RSM), UCSB (ReGCM), and LBNL (MM5-CLM). The main objective was to find the impact of changes in urbanization, vegetation, and irrigation over the Central Valley of California. Current and pre-settlement vegetation and irrigation coverage were used to examine the impact. The three models used in this study provided sufficient similarities and dissimilarities to highlight the uncertainties in impact due to the use of different models. All the models showed that the daily maximum temperature during summer decreased by 3-6 degrees over the Central Valley. There was a difference in the response on daily minimum temperature, which decreased in two of the models and increased in the other. Kanamaru and Kanamitsu (2008b) subsequently studied the RSM response and found that the change in soil conductivity due to wetter irrigated soil was responsible for the nighttime minimum temperature increase. The other models did not show an increase due to the use of different land models. Over urban land areas, urbanization increased both the daily maximum and minimum temperatures during the summertime by about one degree.

The Regional Climate Model Enhancement and Baseline Climate Intercomparison (REBI) was carried out by Miller et al. (2008). The Scripps (RSM), UCSC (RegCM3) and UC Berkeley/LBNL (WRF) modeling groups performed this intercomparison experiment. In addition, Constructed Analogues (CANA) statistical downscaling was also compared. The experiment was set up to downscale NCEP/DOE Reanalysis-2 as the lateral boundary condition. All the models used 10km resolution and downscaled for 10-20 years. The comparison revealed that all the models (statistical and dynamical) had limitations. Nonetheless, they performed as well as other state-of-the-art downscaling systems, and all did a credible job simulating the historical climate of California. The empirically based CANA statistical approach performed at least as well as the dynamical models. Its errors tended to be distinct from those of the dynamical models. The most important limitation of this approach is the very limited set of output variables (near-surface temperature and precipitation) that have so far been predicted using this method. The dynamical models do better at simulating large-scale circulation (as diagnosed by 500 mb heights), surface winds, and near-surface temperatures than parameterized quantities such as clouds, precipitation, and snow cover. Errors in these quantities lead to errors in others; for example, none of the models evaluated here simulated year-round snow cover well. The skill levels of the models varied significantly; WRF-CLM performed best at simulating seasonal precipitation amounts and RSM performed best at simulating near-surface temperature.

The recently completed dynamical downscaling of global Reanalysis data to a much higher resolution over the California region was carried out under PIER sponsorship. The 57-year dynamical downscaling of NCEP/NCAR Reanalysis over California at 10km resolution (CaRD10) was completed in 2006 using the Scripps Global to Regional Spectral Model (G-RSM) system (Kanamitsu and Kanamaru, 2007; Kanamaru and Kanamitsu, 2007). This was the first time such a long-term high resolution dynamical downscaling was performed. The papers describing the system, validation against observations, and comparison with high resolution regional reanalysis over the U.S. (North American Regional Reanalysis, NARR) have been published. The validation clearly showed that the dynamically downscaled analysis is in fact superior to the coarse resolution reanalysis, as it fits better with near-surface station observations. The comparison with NARR revealed that the current data assimilation system cannot use the dense near-surface observations effectively, and the higher resolution (10km) downscaling by RSM outperforms lower resolution (35km) regional reanalysis. The resulting 57-year high resolution analysis has been used in studies of the relation between weather and climate (Kanamitsu, 2007), analysis of long-term linear trend, coastal ocean current, fishery applications (Rykaczewski and Checkley, 2008), wind power applications, and others. The data is publicly available at http://cec.sdsc.edu. Based on the analysis of CaRD10, the physics and numerics of the G-RSM have been improved. This model was used to perform downscaling of current climate for the REBI intercomparison project, and also supplemented the CaRD10 by adding improved analysis for the period 1980-1999, the results of which are also available at the website noted above. The skill of the model was shown to be reasonably high and competitive with other notable regional models.

In follow-on work, an intercomparison of the downscaling of global change projections between different regional models forced by a small number of global warming simulations will be performed. This project is a true extension of the REBI to a global change scenario. Several global simulations will be chosen. The duration of the integration will be 10-20 years and will have exactly the same model configuration as REBI. The objective is to determine the uncertainties due to the regional model. The length of 10-20 years will be sufficient for an initial investigation of the impact of global warming on interannual variability.

PIER supported regional modelers have already started to perform dynamical downscaling of global change simulations using the model and techniques mentioned earlier. Our initial focus is to find the uncertainties in global warming projections due to the differences in the global model simulations used to force the regional model. Since there is some idea of the simulation uncertainties due to the differences between regional models forced by the same external forcing through the REBI experiment, it is possible to arrive at more definite conclusions about the sources of the uncertainties and their ranges. Through this work, it will be possible to provide more quantitative information on the range of changes expected in the future. Aiming at this target, GFDL, MIROC, UKMO, ECHAM, and MRI simulations will be downscaled to cover as many models as possible. The group will make a 5-year downscaling of 4-6 global warming simulations and 4-6 corresponding 5-year present climate simulations. The large scale global simulations performed by MIROC, GFDL, ECHAM, UKMO, and possibly from NCAR and MRI will be used. The A1B scenario (550 ppm CO_2 concentration) from the simulation period 2046-2050 will be used for future global warming simulations and 20C simulations (with CO_2 concentration of 366 ppm) from the simulation period 1974-1977 will be used for present day simulations. Currently, the downscaling of MIROC is in progress.

3.3 Gaps in Research/Knowledge

3.3.1 Change in Mean vs. Change in Interannual Variability

The key elements of the uncertainties in the downscaling of global warming simulations are twofold. The first consists of the uncertainties caused by differences among the models (both global and regional). The second is due to the temporal variability of the global simulations. There are several studies aimed at finding the first uncertainty, but a comparison with the second uncertainty has never been performed. Quantitative evaluations of these two sources of uncertainties are crucial for the interpretation of the uncertainty. They also determine the length of the dynamical downscaling that needs to be performed in order to obtain statistically meaningful results. The analysis of extreme events is also crucially dependent on temporal statistics. It is also noted that interannual variability is an essential component of the California climate.

A major hurdle in examining interannual variability is that the current coupled global models used in global change simulations are not fully able to simulate the interannual variability of the current climate. Some models produce El Niño too regularly and sometimes too often. It is yet to be determined whether other prominent low frequency variabilities such as decadal oscillation and annular mode can be correctly simulated by those models. Due to these considerations, it is essential to perform research on the uncertainties in the simulated "large scale circulation" due to model and to temporal variability. Such research is fundamental to California's climate problems, and progress can be made by simply using the monthly average fields available from AMIP2 and historical IPCC simulations.

3.3.2 Possible Improvements to Models and Modeling Capacity

The improvement of model physics and numerics for the models that participated in the REBI project should continue. The REBI intercomparison project certainly helped to identify crucial problems common to many of the models. Notable problems include the modeling of snow, orographic precipitation, and microclimates, which are currently not handled too well or not resolved well enough in most existing regional models. We should also continue the analysis of the models to identify other problems and find possible remedies. One notoriously difficult problem relevant over the California region is the parameterization of marine stratocumulus. The parameterization is currently strongly based on the statistical nature, not strictly based on the physical principles. Because of this, the simulation of marine stratocumulus suffers from systematic bias, and the uncertainties increase for global simulations (Bony and Dufresne, 2005). The simulation of the transient component is much more problematic, and even the diurnal variation is very poorly simulated by the most advanced current models.

There is opportunity for more coordinated efforts among California and west coast researchers to improve model components. Such efforts can begin by simply comparing parameterizations forced by the same observed forcing. This Single Column Model (SCM) approach is ideal for improvement of parameterizations of snow and marine stratocumulus. For example, results from recent research on marine stratocumulus at the University of Washington and UCLA could be incorporated into regional model codes, and may be very applicable to the California setting.

3.3.3 Coupled Atmosphere/Ocean/Land Regional model

California and its adjacent coastal offshore waters are characterized by complex interactions and feedbacks among the ocean, land, and atmosphere over a wide range of spatial and temporal scales. To realistically model such a system it is necessary to simulate it at the scales at which key interactions occur. Partly because of their coarse resolution, current one-degree-class models used in the Intergovernmental Panel on Climate Change (IPCC) suite of coupled climate simulations typically have serious warm biases in sea surface temperature (SST) in the narrow coastal strip off the west coast of the U.S. Unrealistic simulation of SST in these regions is a reflection of an unrealistic ocean circulation, and also leads to errors in air-sea exchanges affecting the atmospheric circulation over the western U.S. The characteristic spatial scales of the topography in the western U.S are also much smaller than the typical grid spacing of the IPCC models, making it impossible for these models to capture the dramatic spatial variability in precipitation and water resources in the region. High-resolution atmosphere and ocean regional models, developed to focus on local processes, need to be configured so that more processes critical to the coupled system can be directly simulated rather than parameterized. So far, regional climate simulations have been conducted using uncoupled atmosphere or ocean models. Thus, any meso-scale phenomena resolved by atmospheric model (such as Catalina Eddies, fronts, and Santa Anas) cannot affect ocean circulation, and any ocean meso-scale ocean circulation along the California coast cannot affect atmospheric circulation. For the meso-scale analysis of atmosphere and ocean system, which need to be physically and dynamically consistent with each other, it is essential to perform dynamical downscaling/data assimilation of the coupled model. California universities and government lab groups have expertise whereby different regional modeling groups, possibly in collaboration, should move regional modeling systems forward into a regional coupled atmosphere/ocean/land framework, and could also work to include important new biogeochemical, trace gasses, and air quality and hydrologic components.

3.3.4 Comprehensive Data Assimilation

It would be desirable to develop a comprehensive data assimilation system consisting of regional scale atmospheric, land, and ocean models, advanced assimilation analysis components, observation gathering, retrieval and quality control. For the model component, there is already good progress being made in atmospheric, regional ocean, aerosol, air pollution and air quality, urban meteorology, greenhouse gas, fishery, water isotope, fire danger index, and micro-scale hydrology modeling. Ultimately, all of these could be combined into one model (California Regional Environmental Monitoring/Prediction System) (CREMPS). Many other applications models, for water management, agricultural models, disease models, and others can also be attached to this consolidated CREMPS. Use of the recently developed Local Ensemble Transform Kalman Filter (LETKF) method is ideal for data assimilation of atmosphere and ocean, and it would be relatively straightforward to expand it to the analysis of trace gasses, aerosols, water isotopes, ocean biomasses, and many other relevant fields for global environmental monitoring and prediction. An additional essential component in this effort would be to include a variety of observed retrieval of relevant parameters from satellite observations. Lastly, large computer resources are essential for this type of facility to function.

3.3.5 Computer resource availability

Climate model simulations require considerable computer resources for computations, storage, and distribution of model output and other data. Individual research groups obtain their own computer resources from NSF or DOE by writing additional proposals. Some research groups use their own in-house computer facility. Unfortunately, these resources are far from satisfactory and most of the experiments are performed in smaller areas and for shorter periods, occasionally sacrificing the use of more complete physical processes for economical reasons. More plentiful computer resources would greatly enhance the modeling activity and raise the standard of the research.

3.4 Recommendations for California Regional Model Development

- Continue the model development and intercomparisons, such as the REBI Expand this effort to perform an intercomparison of the downscaling of global warming simulations. This project should be accompanied by more detailed analysis than was possible during the first REBI project, providing skill mask, model systematic errors, and ensemble averaging.
- Conduct dynamical downscaling of multiple-global model simulations to identify uncertainties in results due to global model simulations. Compare the uncertainties due to the global model and the uncertainties coming from interannual variability. Compare dynamical downscaling results with (limited variables) statistical downscaling results. Reevaluate the uncertainties obtained in 3.1 above.
- Continue improving regional model physics. Particular emphasis should be placed on snow model and marine stratocumulus parameterizations, and attention should be given to focus upon processes that are most crucial to California results. Continued attention should be given to determining which aspects of the physics result in the largest inter-model differences over California.
- Develop and evaluate a coupled regional atmosphere/ocean/land model for the California region.
- Conduct modeling experiments with "offline" models, but linked to the forcing of atmosphere and coupled atmosphere/ocean/land models, regional and global, to simulate relevant aspects of California's climate and impacts; e.g., its physical hydrology, water resources, coastal waves, air quality, and ecosystems.
- Work with modeling teams to obtain computer resources for modeling activities.

- Continue efforts to collaborate across modeling, analysis, prediction, and diagnostics for the California region. Move towards a comprehensive data assimilation model that incorporates multivariate environmental processes.

4.0 Diagnostics

Decision support, e.g., for matters relating to California energy and water issues, is increasingly requested from the climate community. The observations and modeling system should be designed to integrate climate and its impacts, risk assessment, and adaptation/mitigation, and should be suited to inform short-range problems and predictions as well as climate change decision making. Detailed projections of climate change are needed to inform the State's social and natural infrastructure and its vital economic sectors, and better understand sensitivities, vulnerabilities to change, and conditions that drive water, energy supply and demand, air quality, human health impacts, and many other elements that are crucial to California. In particular, the modeling and analysis conducted in this program area must be brought to bear on understanding and predicting a range of extreme events including heat waves, floods, and drought.

Climate change adds complexity to these decisions because of the lengthy time scale required to plan and construct additions to the energy and water infrastructure and the long time period over which such projects are operational. There are many aspects of water resources, energy resources, agriculture, ecosystems, and other sectors that are linked, particularly because both supplies and demands for energy and water are affected by large scale and regional climate patterns. Changes in western U.S. temperatures, snowpack, and the timing of river runoff are already significant, but are projected to be much greater in coming decades, when projects being planned today will be used, and resource requirements for growing populations and new developments will likely increase. Extreme events, though rare, are a critically important part of the climate that are still under investigation (Nieman et al., 2007; Gershunov and Duville, 2007; CCSP, 2008). Climate change across the western U.S. will affect hydropower, irrigation, peak and average energy demand, the intensity of flooding, and other energy and water issues. Patterns of energy demand will change across the western U.S. as the region warms and the air-conditioning season expands earlier into the spring and later into the autumn. Regions that previously experienced low air-conditioner use will likely increase the installed base in response to higher daily maximum temperatures. Hydropower availability and irrigation demand will change as the timing of runoff from melting snowpack changes and hotter summers lead to greater evaporation and dryer soil conditions. Using improved atmospheric and hydrologic models, the ability exists to estimate the tendency and likely magnitude of such changes, information valuable to a variety of planning and long-term management activities.

It is important to understand that increasing greenhouse gases will increase temperatures and alter the hydrologic cycle through increased water evaporation and precipitation, shifts in precipitation from snow to rainfall, and sea level to rise. These impacts will necessarily affect not only energy but also agriculture productivity and water quality and supply. How we predict and then manage these changes will have both regional and global consequences.

4.1 Some important topics that should be addressed by analysis and diagnostics

- Climate Change Detection in California region—where, when, how much?
- Climate Change Attribution in California region—natural variability or related to anthropogenic forcings?
- Understanding and quantifying uncertainties within and among climate change projections and expected impacts
- Understanding climate linkages within the climate and hydrologic system
- Understanding climate impacts, along with other factors in present-day and future changes
- What are the best predictors of long-term climate variability in California and are these also the best predictors of long-term climate change influences?
- What is the role and future of Pacific (and global) climate modes like ENSO, as affects California?
- How much of projected California climate change reflects local radiative changes and how much will be advected into the region from global responses?
- How will the impacts of climate change cut across multiple sectors?
- How does the 3-dimensional structure of winds, humidity, and other air mass characteristics affect precipitation, e.g., in high precipitation storm events?
- Will major storms change in frequency or strength?
- What is the aerosol budget? How do aerosols affect precipitation and snowmelt?
- How has vegetation changed over the last century, how will vegetation change as climate changes, and how will that affect climate and hydrology?
- How will urban climates change as climate changes? Which urban centers are likely to be most impacted by warming and other climate changes?
- How do ocean and land feedbacks affect weather and climate? What is the role and future of coastal upwelling and coastal clouds and their effects on coastal and inland climates?
- How will climate warming and other climate change effects vary from the coast to the interior and from low to high altitude settings in California?
- Which critical micro-climates will respond adversely to climate change?
- Will droughts increase in frequency, intensity, or duration? How will atmospheric demands for evaporation and transpiration change?
- Will floods increase in frequency and intensity? What watersheds are most vulnerable to increases in flooding?
- How fast and how much will sea level rise? How will this couple with storms, waves, and tides to affect California coast and estuaries?

- Will duration and intensity of heat waves increase? What is the future of smog-trapping atmospheric inversions? How will this affect human health and demand for energy and water?
- How will regional and global climate change impacts, beyond State borders, affect California?

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